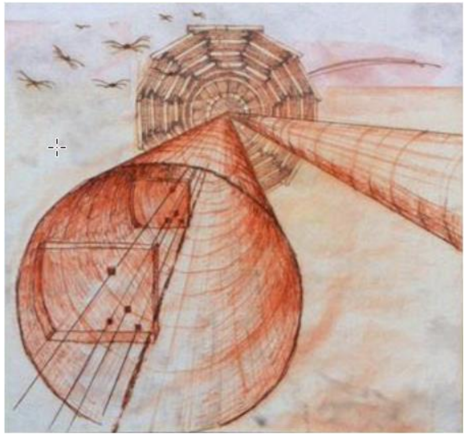

Performance and prospects of the PPS tracking system

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on behalf of the CMS and TOTEM Collaborations

15th "Trento" Workshop on Advanced Silicon Radiation Detectors

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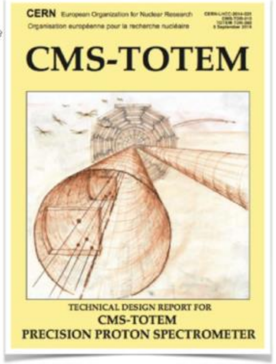
Outline

- Project overview
- Experimental apparatus
- PPS 3D pixel tracker
- 3D pixel tracker performance in LHC-Run2
- Prospects for LHC-Run3

The CT-PPS project – now PPS!

Conceived as a common CMS-TOTEM project, CT-PPS (CMS-TOTEM Precision Proton Spectrometer) was approved in Dec. 2014 by LHCC and CERN Research Board

Since April 2018, CT-PPS is a standard sub-detector of CMS, named PPS

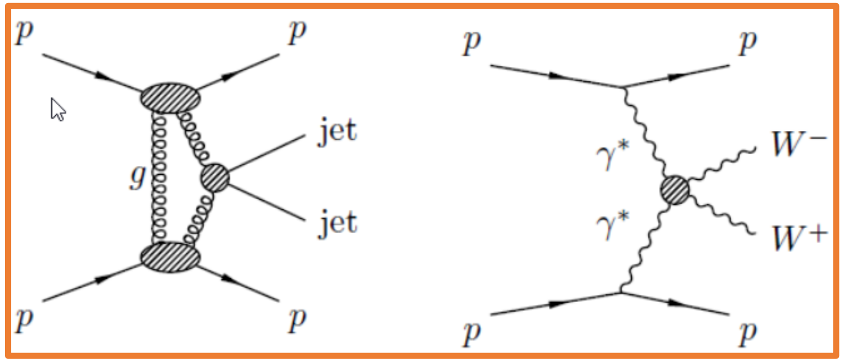


CERN-LHCC-2014-021

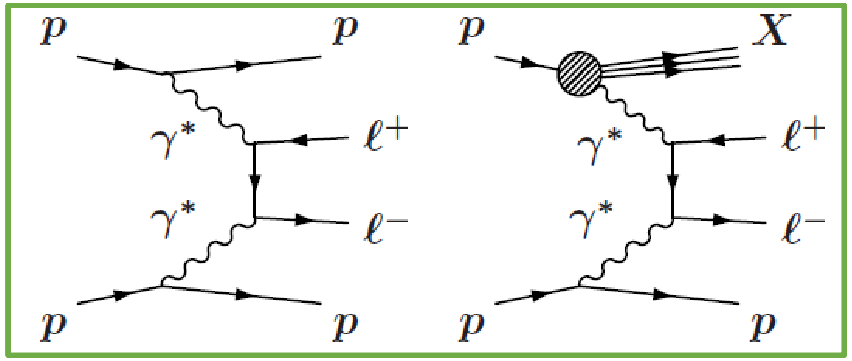
The PPS physics program focuses on Central Exclusive Production (CEP) processes of the type:

$$\mathbf{pp} \rightarrow \mathbf{p\,X\,p} \qquad \text{X = high-}E_T\text{ jets, WW, ZZ, }\gamma\gamma\ldots$$

where both protons remain intact in the final state



Processes studied in detail for the CT-PPS TDR [CERN-LHCC-2014-021]



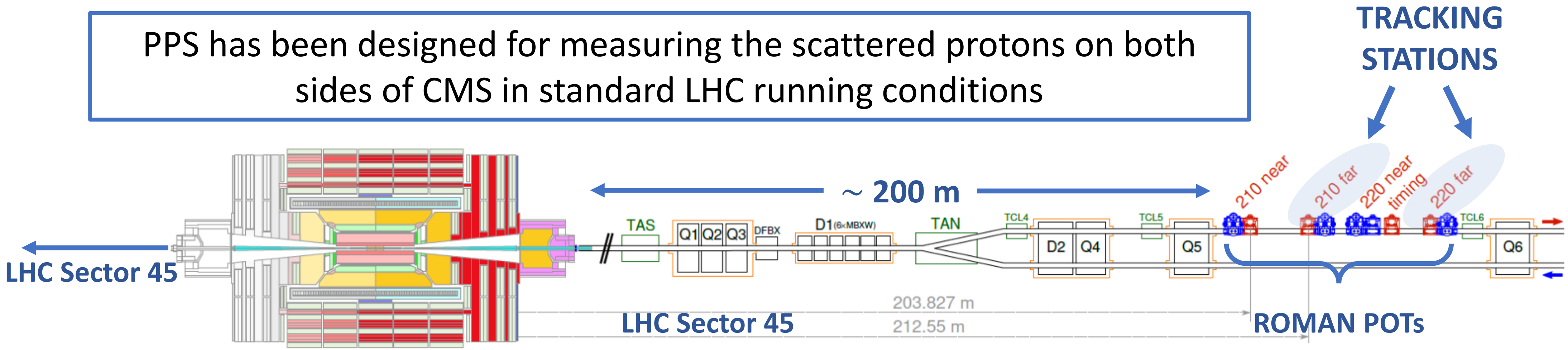
PPS first publication, JHEP07 (2018) 153

The Precision Proton Spectrometer

PPS is a magnetic spectrometer that uses LHC magnets to bend diffractive protons out of the beam envelope and measure their kinematics

✓ Constrain the event kinematics by matching the momenta of the central system (X) and the leading protons

PPS has been designed for measuring the scattered protons on both sides of CMS in standard LHC running conditions



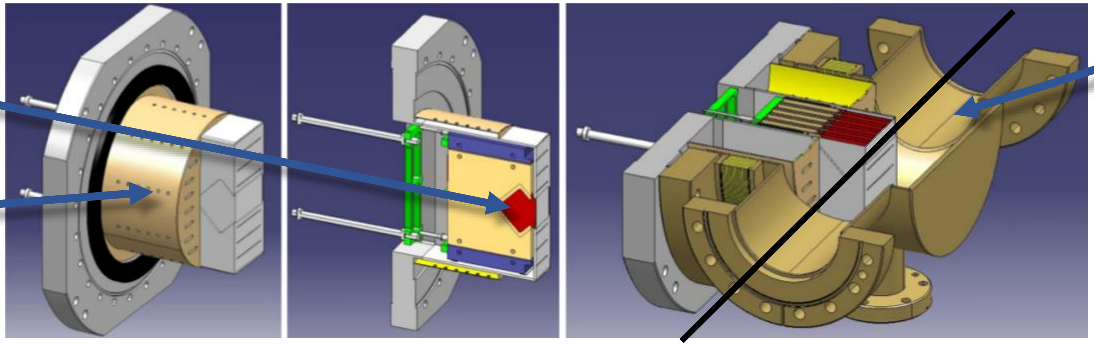
Two complementary measurements:

➢ **Tracking detectors** measure the proton displacement w.r.t. the beam, which is translated into proton fractional momentum loss (ξ) thanks to the knowledge of the beam optics

➢ **Timing detectors** are used to disentangle pile-up

Tracking detectors: experimental challenges

- **Roman Pots need to operate at few mm from the beam to maximize acceptance**
  - RF shielding installed to limit the impedance caused by the RP insertion

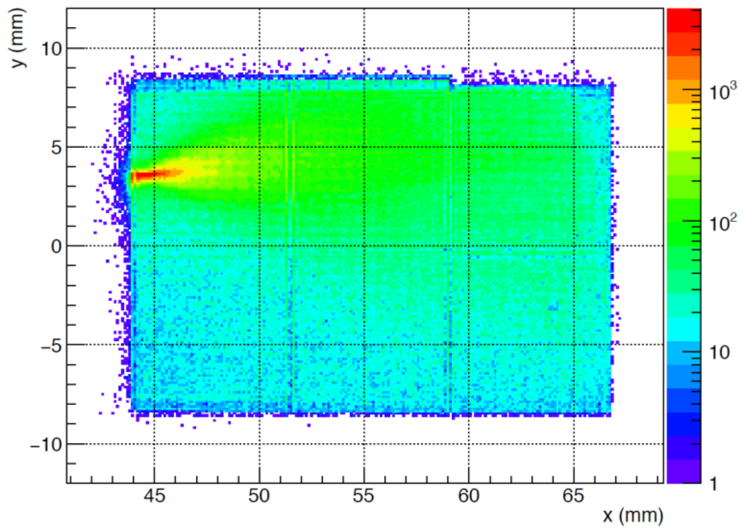


In 2017-18 PPS RPs inserted at **$12\sigma_{beam}$ + 0.3 mm ($\sim$ 1.5 mm)** distance **from the LHC beam**

- **Detectors must tolerate high levels of non-uniform irradiation**
  - Proton flux up to $\sim 5 \cdot 10^{15}$ protons/cm^2 for 100 fb^{-1}
    Dose: $\sim$1.61 Mrad/fb^{-1}

- **Spatial resolution:** $\sim$ 10-30 μm
- **Detectors must be fully efficient as close as possible to their mechanical edge**

Proton track distribution – 45-220 FAR



Project overview
Experimental apparatus
PPS 3D pixel tracker
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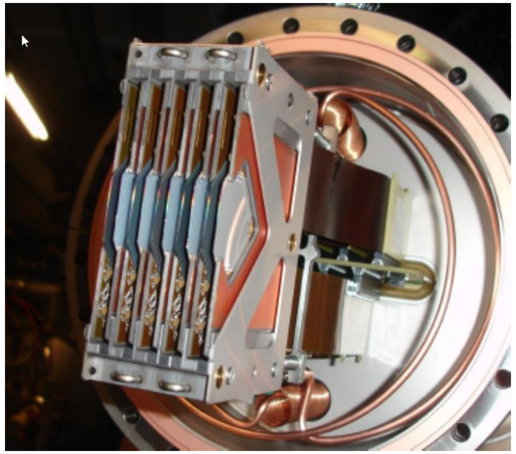
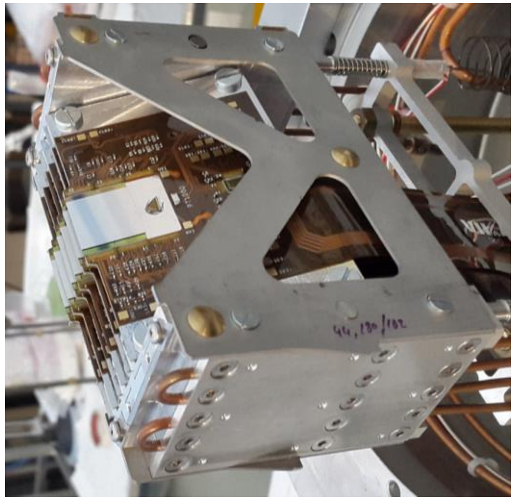
PPS tracking configurations in LHC-Run2

Data taking with CMS in 2016, 2017 and 2018 with different detector configurations

2 Tracking RPs on both sides of CMS



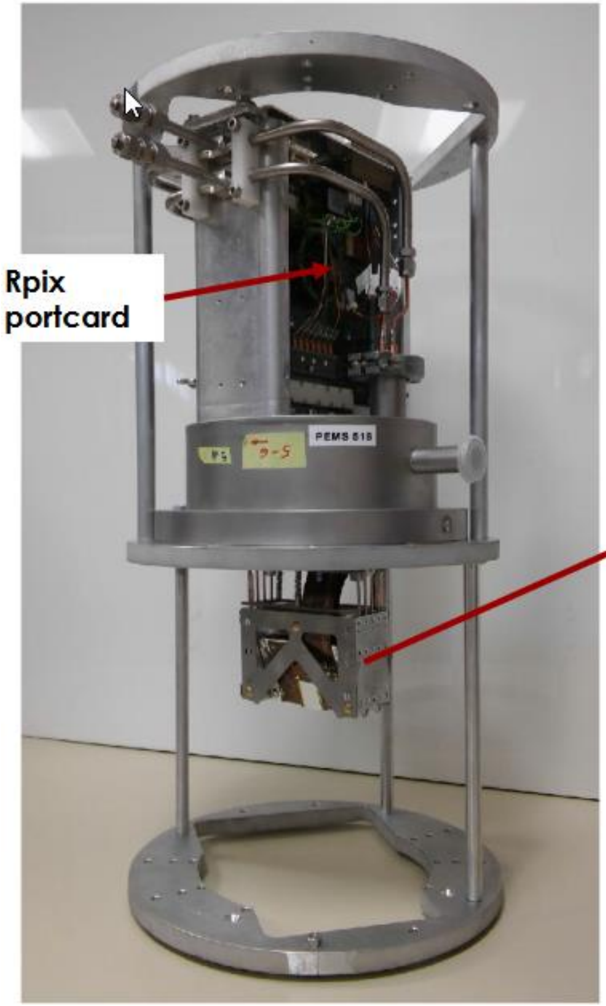


Exploratory phase	Legacy TOTEM strip detectors	Strips + 3D pixels	3D pixels
2015	**2016**	**2017**	**2018**
	$L_{INT} \sim 15\ fb^{-1}$	$L_{INT} \sim 40\ fb^{-1}$	$L_{INT} \sim 60\ fb^{-1}$
Data recorded with tracking RPs inserted	39% of the data recorded by CMS	88% of the data recorded by CMS	93% of the data recorded by CMS

Very high stability in both 2017 and 2018

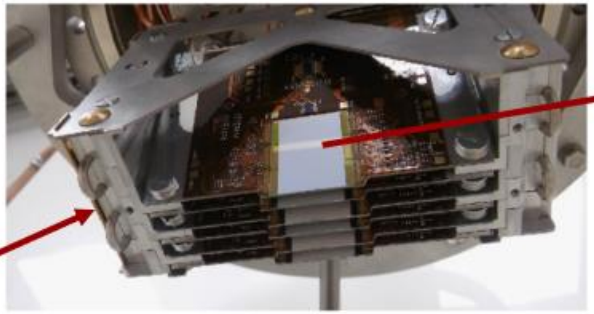
PPS integrated luminosity in LHC-Run2: $\sim$115 fb^{-1}

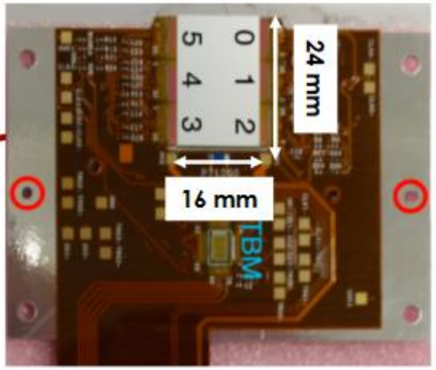
PPS pixel tracking detector



Each station contains **6 detector modules**, tilted by 18.6° to improve resolution

- **3D pixel silicon sensors** are read out with **4 or 6 PSI46dig ROCs** based on the sensor size (same as in layer 2-3-4 of the CMS Phase I pixel tracker)





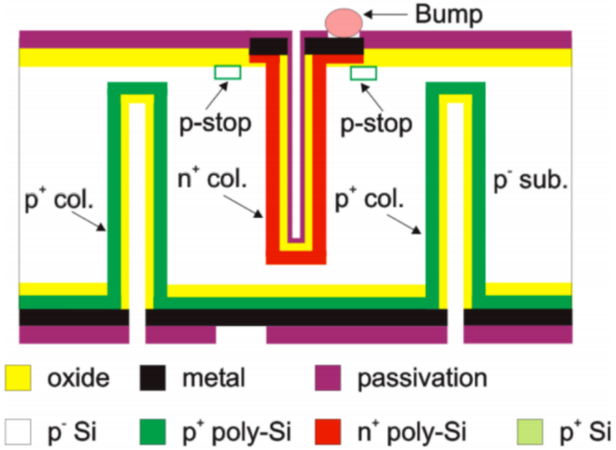
- Modules are wire-bonded to a flex circuit connected to the RPix portcard (interface between modules and DAQ boards)
- **Same data read-out** (FED) and control (FEC) boards used for the Phase I upgrade **of the CMS pixel tracker**
- Mechanics and cooling adapted from TOTEM tracking system
- **Operation at ~-20 °C and in vacuum** (P < 20 mbar)

PPS silicon 3D pixel sensors

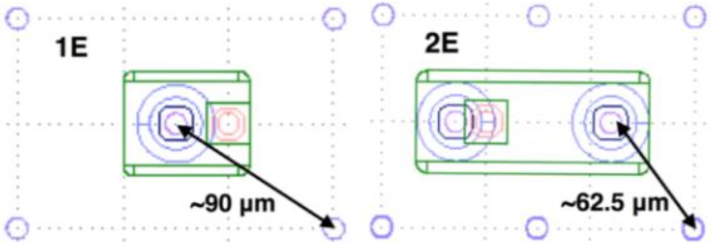
3D sensor technology chosen because of its high radiation hardness and possibility to implement slim edges

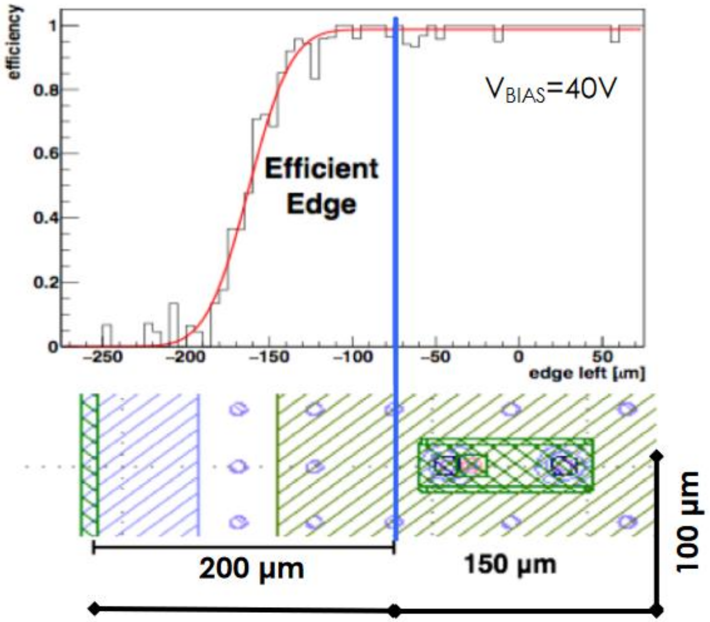
Sensors produced by CNM with double-sided process and non-passing-through columns

- Pixel size: 150x100 μm^2
- Sensor thickness: 230 μm
- Column depth: 200 μm
- Column diameter: 10 μm
- Depletion voltage: ~5-10 V



1E and 2E electrode layout





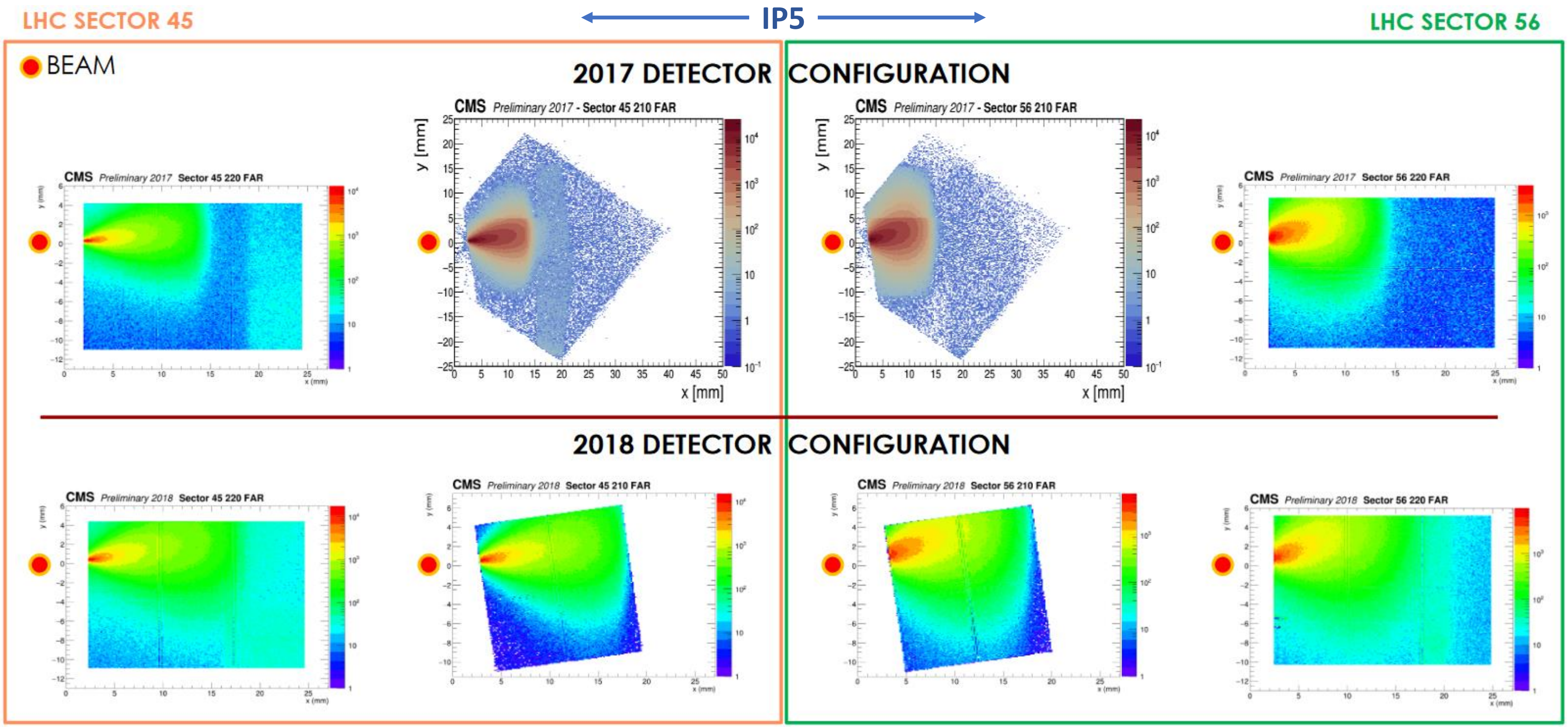
3D sensors bump-bonded to the PSI46dig ROC were extensively tested in laboratory and with beam, at FNAL [1]

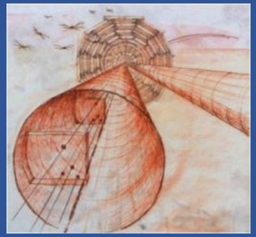
✓ 200 μm slim edge made of triple p-type column fence. **Reduced to ~50 μm by increasing the bias voltage** (for 2E type)

✓ **Spatial resolution for 2E**(1E) electrode configuration, with sensors tilted by 20°: **22 μm** (25 μm)

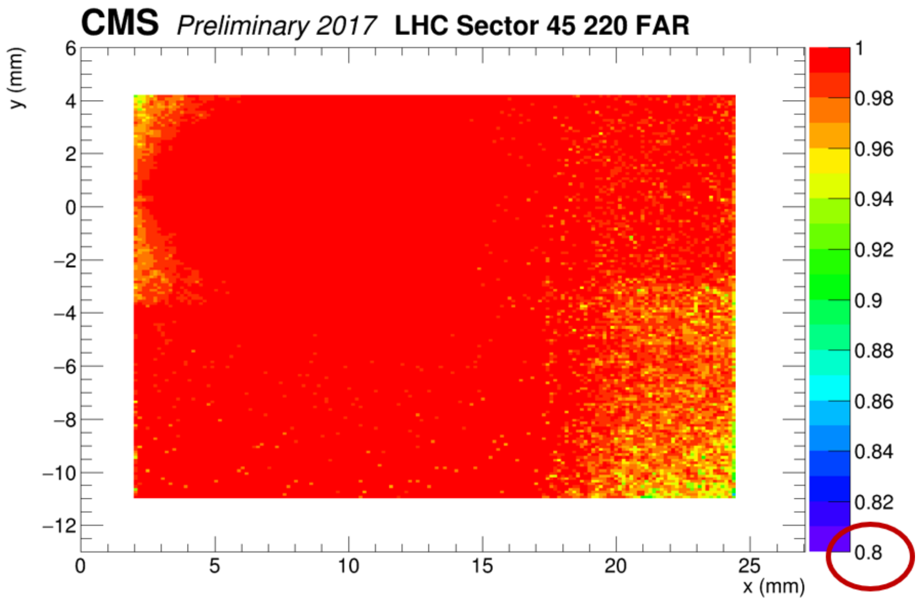
[1] F. Ravera, *The CT-PPS tracking system with 3D pixel detectors*, Pixel 2016 Workshop

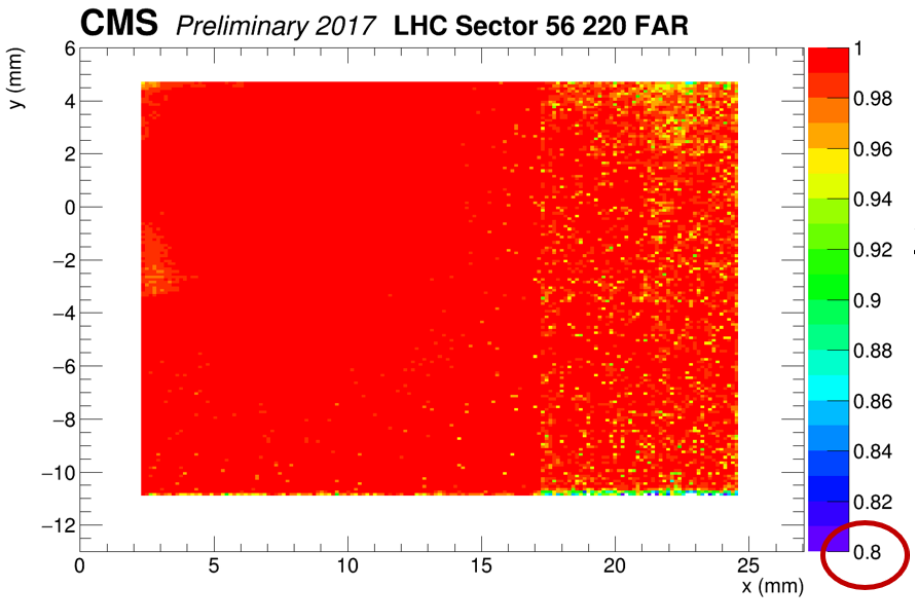
2D track impact point distributions





PPS 3D pixels performance: efficiency





RP efficiency at the beginning of 2017 data taking

Similar results in 2018

Overall very good performance – **average efficiency above 99%**

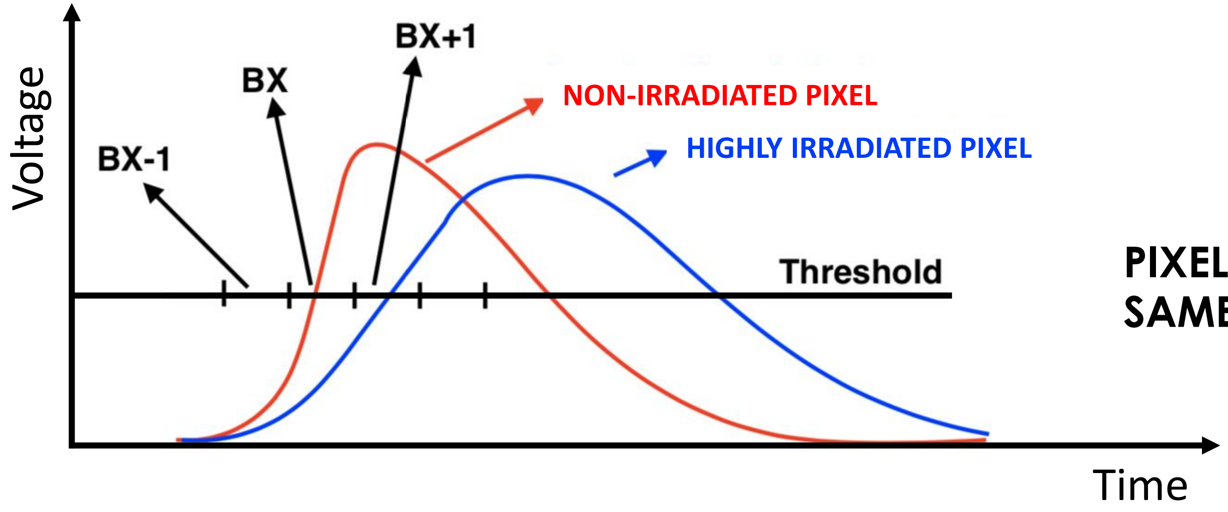
The lower efficiency region visible in the right part of the two maps is due to the fact that both RPs have one 2x2 plane not covering that region, and to the presence of malfunctioning ROCs on other planes

Less than 0.05% bad/noisy pixels

Radiation effects on the ROC

Pixel ROC PSI46dig **not optimised for non-uniform irradiation.**

Non-uniform irradiation causes a difference between the analog current supplied to the most and the least irradiated pixels.



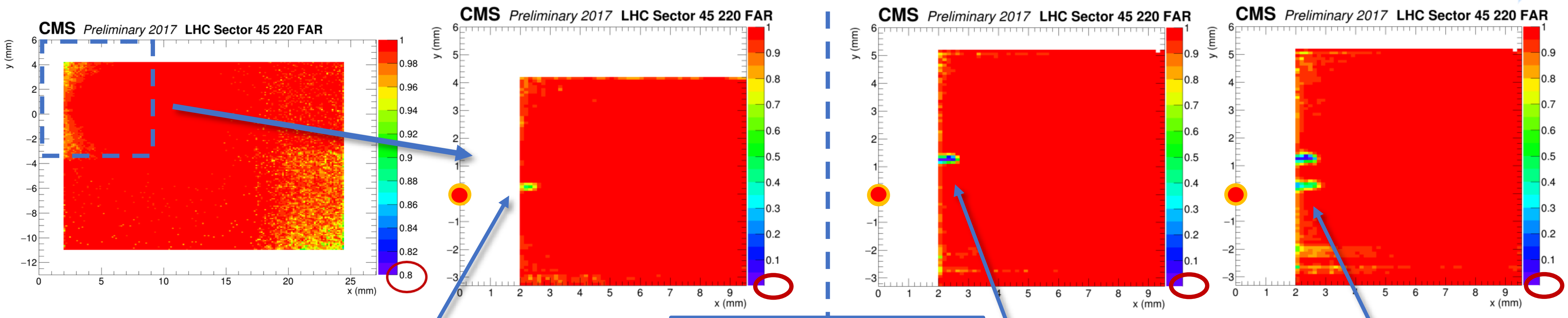
PIXELS NOT RESPONDING IN THE SAME 25 ns CLOCK WINDOW (BX)

- ✓ Irradiation studies performed before installation at LHC showed that after a dose corresponding to L_{INT} (LHC) ~8 fb^{-1} the drift of the useful time window for signals in most irradiated pixels exceeds 25 ns
- ✓ To mitigate the impact on the data quality, the tracking stations were lifted up during LHC technical stops (TS) to shift the occupancy maximum away from the damaged region.

RP efficiency vs. integrated luminosity (2017)

Evolution of the RP efficiency map in the detector region closest to the beam for LHC Sector 45

BEGINNING OF DATA TAKING — 8.8 fb^{-1} — TS — 18.9 fb^{-1} — 29.5 fb^{-1}



Lower efficiency caused by the radiation damage

RP moved upwards by 1 mm

Damage area effectively moved away from the most irradiated region

As the integrated luminosity increases**, a second damage region appears** at the new occupancy maximum

Detectors in LHC Sector 56 suffered smaller radiation damage (barely visible in the maps) **because of the different irradiation profile**

Project overview

Experimental apparatus

PPS 3D pixel tracker

3D pixel tracker performance in LHC-Run2

Prospects for LHC-Run3

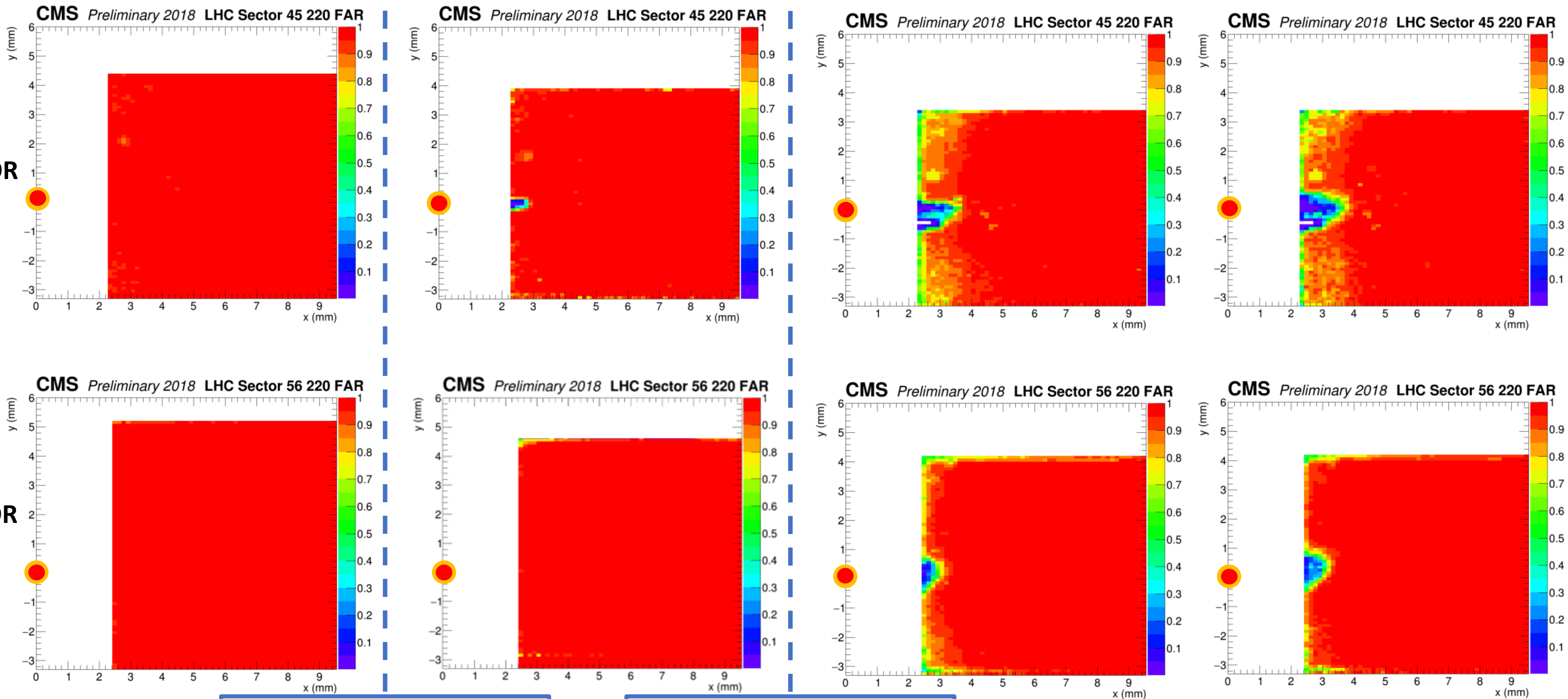
RP efficiency vs. integrated luminosity (2018)

Evolution of the RP efficiency map in the detector region closest to the beam for RP 220 FAR (worst case)

BEGINNING OF DATA TAKING | TS | 21.0 fb^{-1} | TS | 50.3 fb^{-1} | 57.8 fb^{-1}

LHC SECTOR 45

LHC SECTOR 56



RP moved downwards by 0.5 mm

RP moved downwards by 0.5 mm

Project overview

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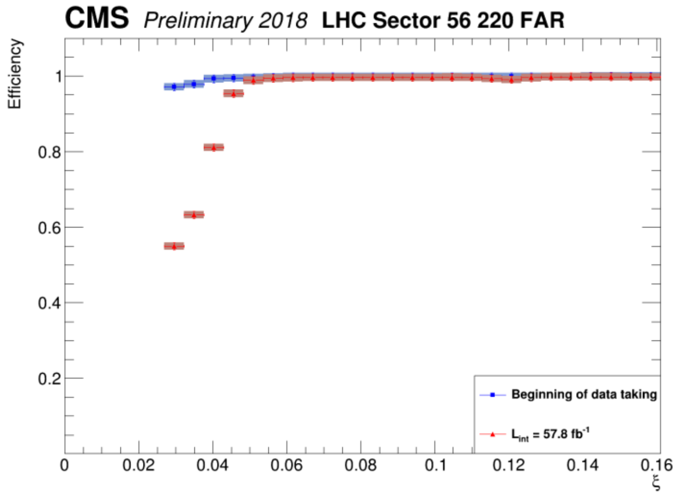
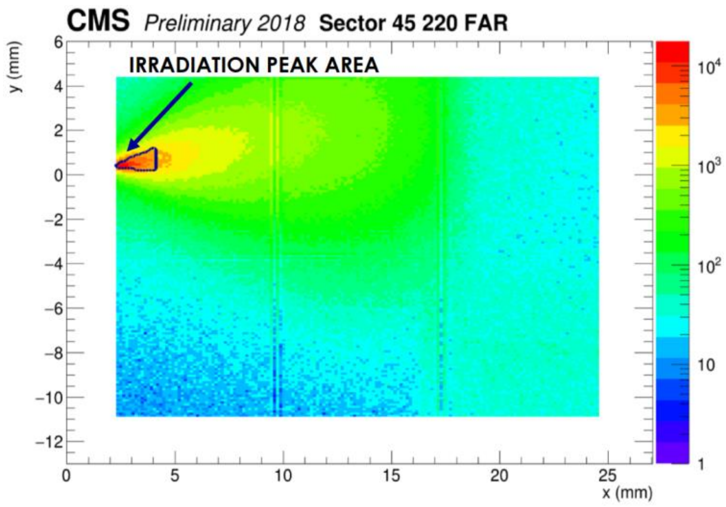
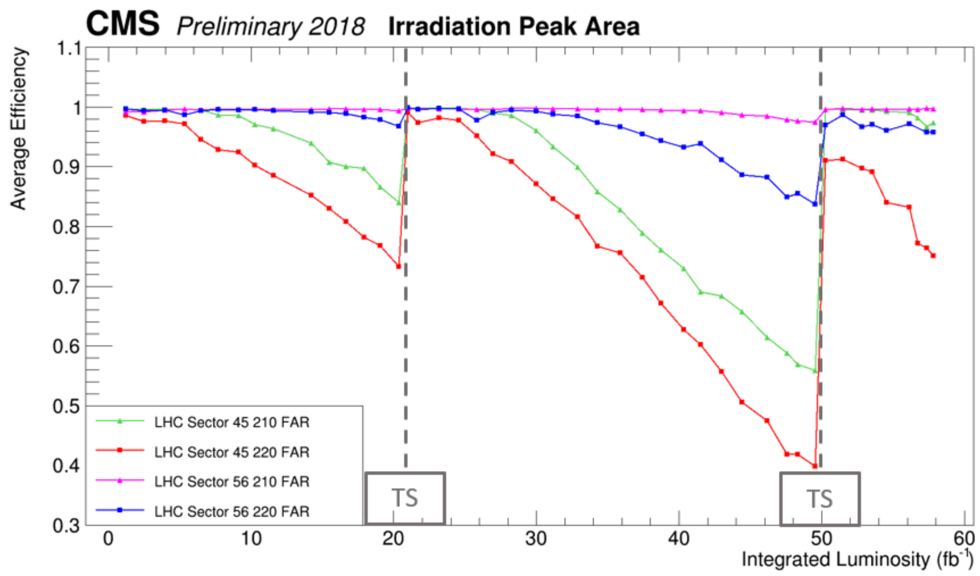
Effects of radiation on RP efficiency (2018)

The **radiation damage** in the highest irradiated region **directly affects the detector low-ξ performance**







Average efficiency calculated every ~ 1 fb^{-1} in the critical region (irradiation peak area)

- **Drop in the efficiency due to irradiation clearly visible in the critical region**
- **Recovery after each Technical Stop** (TS) because of the vertical movement of the RPs

Plot to be used as a monitoring tool during LHC-Run3 data taking

Project overview

Experimental apparatus

PPS 3D pixel tracker

3D pixel tracker performance in LHC-Run2

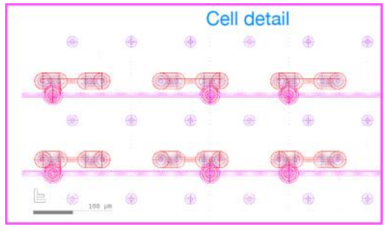
Prospects for LHC-Run3

PPS prospects for LHC-Run3

PPS will take data fully integrated in CMS during LHC-Run3 (2021-2023)

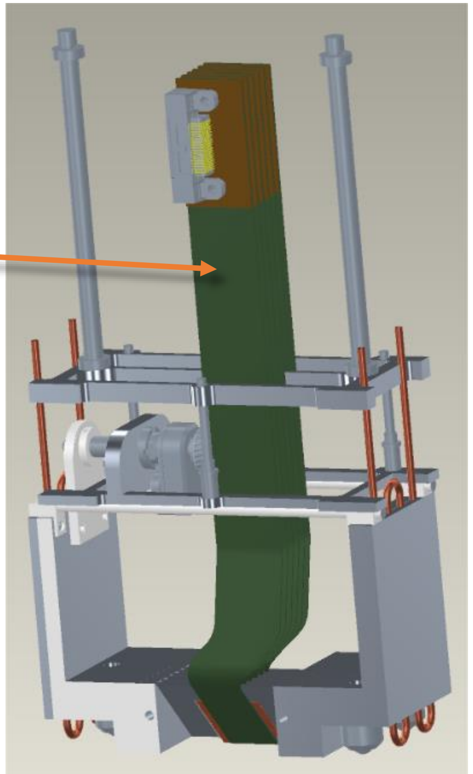
Tracker system in LHC-Run3

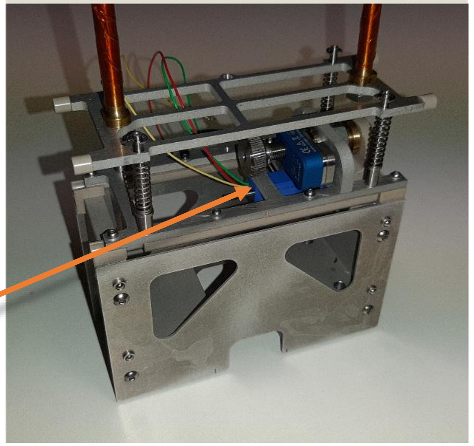
- 2 Roman Pots per side, at 210 m and 220 m
  - 6 detector planes per RP (same as 2018)
- **New 3D silicon pixel sensors** in production at FBK
  - ✓ Single-sided technology
  - ✓ 2x2 sensor geometry
  - ✓ Sensor active thickness: 150 μm
  - ✓ 2E electrode configuration



- **PROC600 ROC** (same as the layer 1 of the CMS central pixel tracker)
- **New flex circuit** design (very similar to LHC-Run2 version)
- New detector package with **internal movement system** (piezo actuators)
  - Better distribute the radiation damage
  - 6 mm range (500 μm steps) to withstand up to ~50 fb^{-1} with minimal efficiency degradation

New flex circuit





Piezoelectric motor

Conclusions

PPS has proven the feasibility of operating a near-beam proton spectrometer at a high-luminosity hadron collider and **has collected ~115 fb^{-1} of data** during LHC-Run2

PPS 3D pixel tracking system has been **successfully operated** in 2017 and 2018 with **very high stability and overall good performance** despite the high and non-uniform irradiation

The preparation of the new detectors for LHC-Run3 is ongoing:

- **New 3D pixel sensors are currently in production**
- **An internal piezo-actuated movement system is in its final testing phase** and will allow to maintain higher performance throughout LHC-Run3
- A **rich physics programme** lies ahead, with multiple final states to be studied and explored

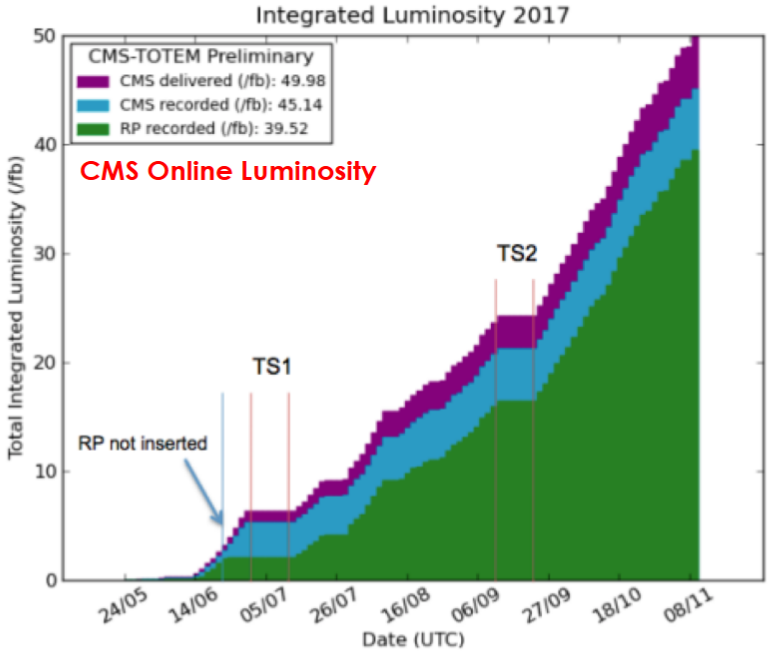
Thanks for your attention

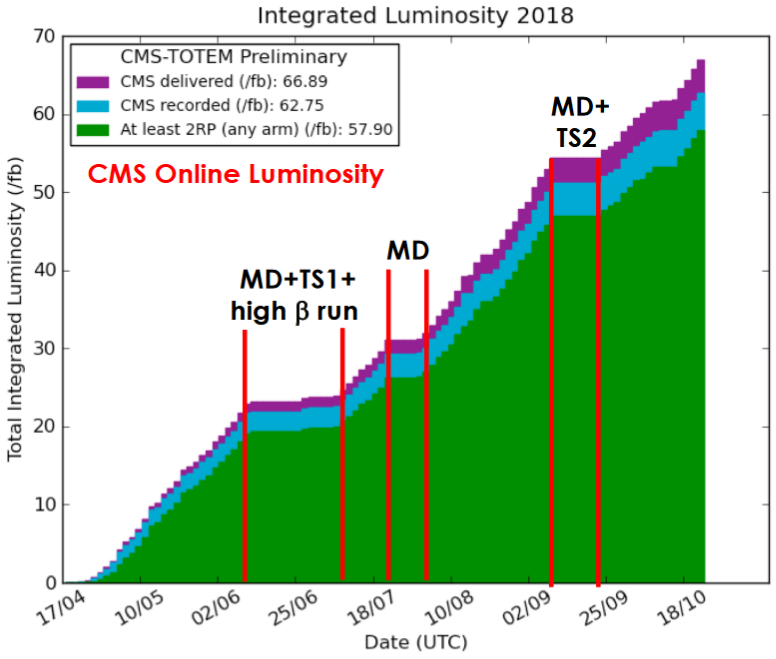
Backup material

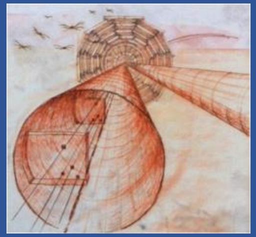
2017 and 2018 data taking

PPS collected:

- ✓ ~88% of the full CMS 2017 statistics
  - ➢ ~40 fb^{-1} with RP data
- ✓ ~93% of the full CMS 2018 statistics
  - ➢ ~60 fb^{-1} with RP data

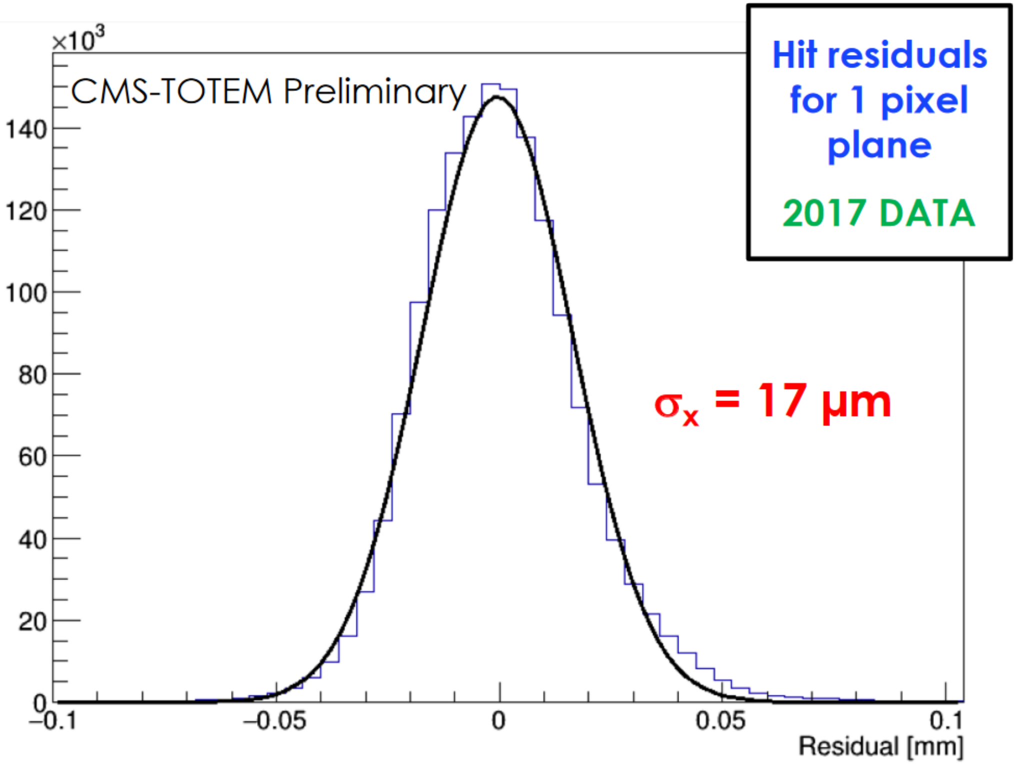






Tracker performance: hit residuals

Hit residuals for single planes are evaluated w.r.t. the local track reconstructed in the pixel RP

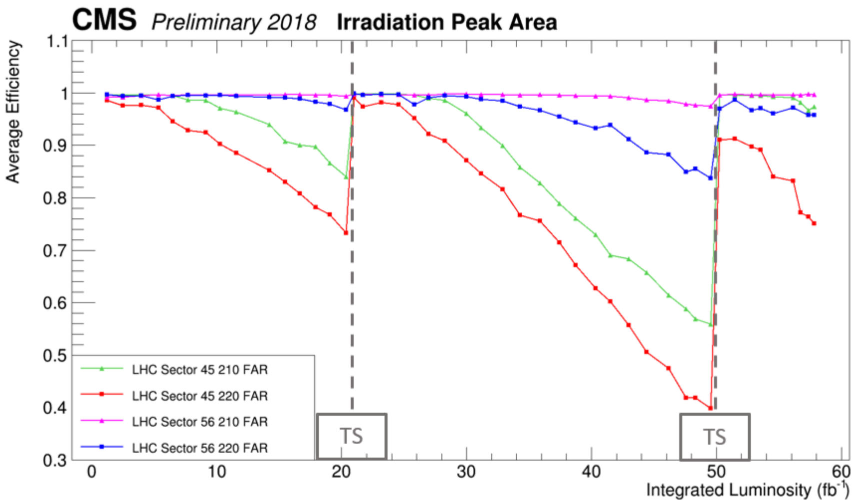


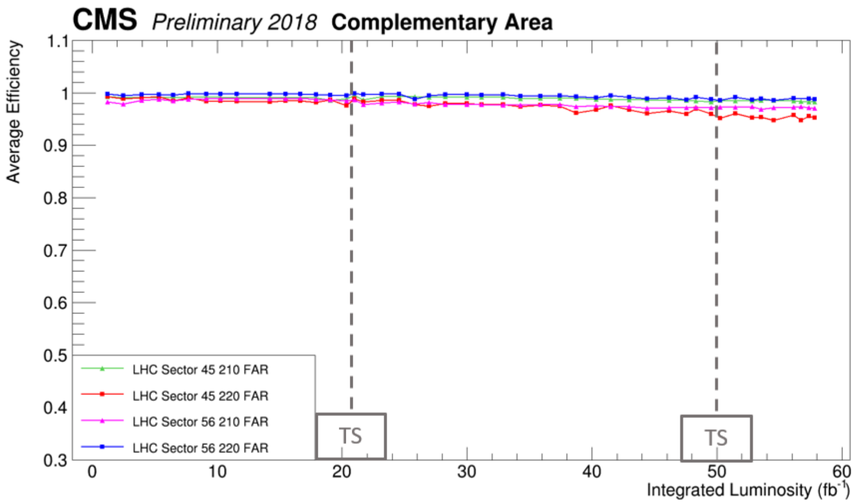
- Residuals consistent with beam test results
- Similar results in 2018

✓ The pixel tracker works accordingly with expectations

✓ Track resolution under final evaluation (~20 μm)

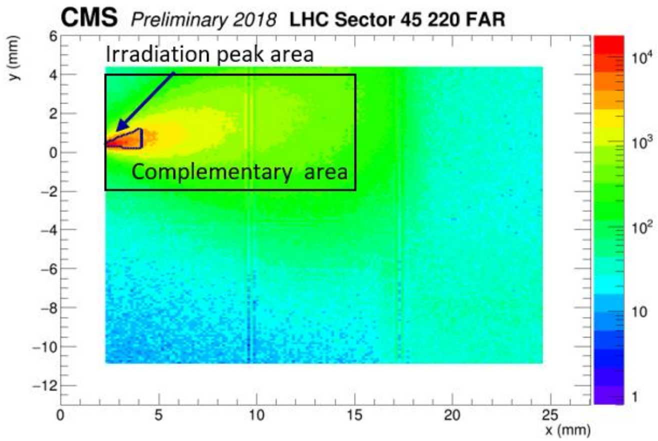
Radiation effects on RP efficiency in 2018





Average efficiency calculated every $\sim 1\ \mathrm{fb}^{-1}$:

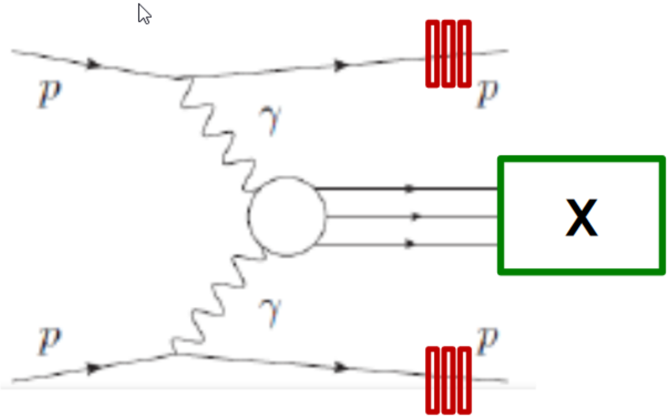
- in the critical region around the irradiation peak (left plot)
- in the complementary region (right plot)

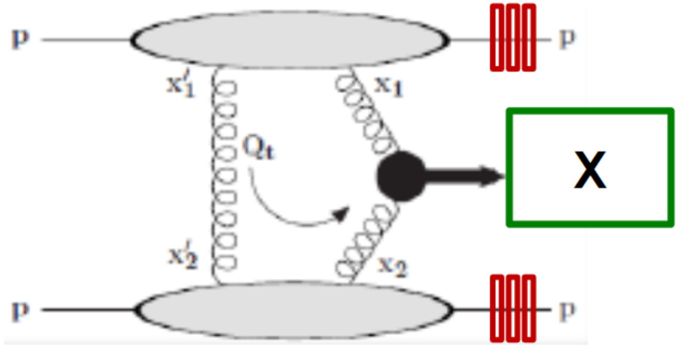


A drop in the efficiency due to irradiation is clearly visible in the critical region; here, the recovery after each LHC technical stop (TS) is due to the vertical movement of the RPs.

The average efficiency in the complementary area remains high and almost constant during the whole data taking. The small slope observed after the first TS is due to the damage exceeding the defined irradiation peak area. This effect is more pronounced for RP 220 FAR in sector 45, as also clearly visible in the efficiency map.

The experimental strategy





- High-p_T system (X) detected by the CMS central detector, scattered protons detected by **PPS**
- Requiring the momentum balance between the central system and the detected protons creates **strong kinematical constraints**
- **Central system mass is measured via the momentum loss of the two protons**

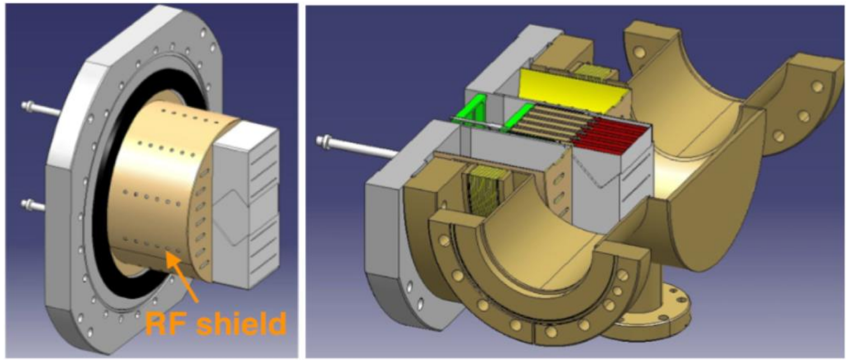
$$\boxed{M_X = \sqrt{s \cdot \xi_1 \cdot \xi_2}}$$

ξ: fractional momentum lost by the proton

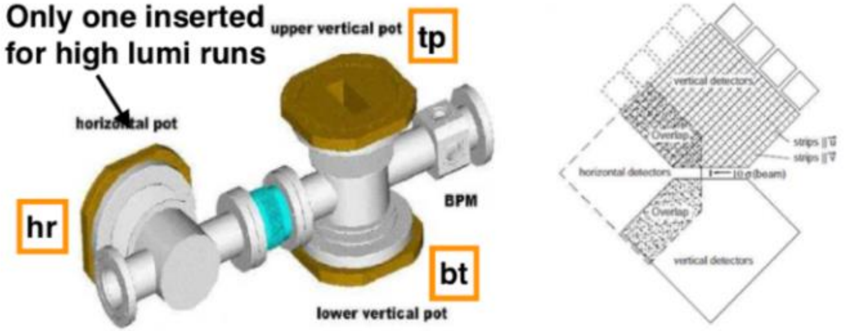
Measurements to be performed in **standard LHC high luminosity** conditions

Roman pots

RP for tracking stations

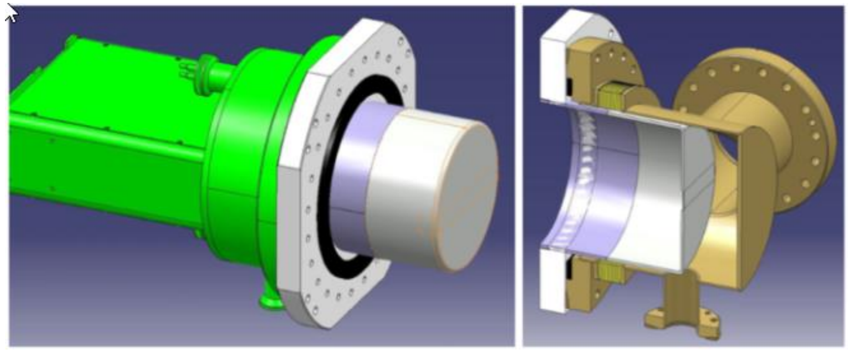


Each station includes 3 RPs



Tracking RPs **equipped with a thin window 150 μm thick towards the beam**

RP for tracking stations



Cylindrical RP specifically designed for PPS to limit the effects on the beampipe impedance and host larger detectors

Equipped with **a 300 μm thick window towards the beam** (larger thickness is required to compensate the pressure gradient on the larger window)

No vertical stations, alignment is performed by propagating tracks from the tracking stations